

Ultra-Steep Spectrum Radio Galaxies at Hy Redshifts

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Abstract. Radio sources have traditionally provided convenient beacons for probing the early Universe. Hy Spinrad was among the first of the tenacious breed of observers who would attempt to obtain optical identifications and spectra of the faintest possible ‘radio galaxies’ to investigate the formation and evolution of galaxies at hy redshift. Modern telescopes and instruments have made these tasks much simpler, although not easy, and here we summarize the current status of our hunts for hy redshift radio galaxies (HyZRGs) using radio spectral and near-IR selection.

1. Hy Z Radio Galaxies: Why?

The first optical identifications of (bright) radio sources with (faint) galaxies were made when Hy Spinrad was still a teenager (Windhorst 1999; these proceedings). After that it was soon realized that the ‘invisible’ universe of radio sources provided convenient beacons to locate very distant galaxies and thus might be used to study their formation and evolution. As so eloquently described by

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several of Hy's colleagues, collaborators and ex-students in these proceedings, he became an early key player in these distant galaxy hunts.

For most radio astronomers in those days the Universe stopped at the POSS limits. Surely, many radio sources could not be identified, but so what? It just confirmed that the Universe was bigger than the biggest optical telescope, but ... not bigger than the biggest *radio* telescope! Occasionally Hy would write letters to Leiden Observatory radio astronomers with requests of radio maps and accurate positions. When provided he would spend many hours using one of the world's then finest telescopes at Lick Observatory, to obtain optical identifications and spectra of these HyZRG candidates (presumably squeezed in between observations of standard stars for Jim Liebert; these proceedings). How foolish this seemed, to some of us (WvB).

Since then extraordinary progress in the development of optical and near-IR detectors, larger telescopes, and better selection techniques have resulted in discoveries of radio galaxies at increasingly higher redshifts. Paradoxically this task was eased by the discovery, first by Hy and his collaborators, that the Ly α emission line was very strong in radio galaxies and could easily be detected in < 1 hr integrations with 3m-class telescopes (Spinrad et al. 1985), provided that the redshifts would be high enough ($z > 1.6$) so that Ly α would enter the observable optical window.

It has now become clear that HyZRGs are both a boon and a curse for students of galaxy evolution. A boon because the near-IR Hubble $K - z$ relation for radio sources appears well represented by the predicted 'passive' evolution of massive ($5 - 10 L_*$) galaxies with high formation redshifts (Lilly & Longair 1984; Eales et al. 1997; Best et al. 1998; van Breugel et al. 1999), despite the effects of k-correction and morphological evolution (van Breugel et al. 1998). No matter the reason for this relationship, it suggests that radio sources might be used to find massive galaxies and their likely progenitors out to very high redshift. This method was first successfully used by Lilly (1988) to identify the HyZRG B2 0902+34 at $z = 3.395$. Deep spectroscopic observations of a few relatively weak radio sources (but still of the powerful double FRII class!), where the AGN do not affect the rest-frame UV as much (see below), have shown directly examples of radio galaxies at $z \sim 1.5$ with old ($\gtrsim 3.5 - 4.5$ Gyr) stellar populations with implied formation redshifts $z_f > 10$ (e.g., Spinrad et al. 1997).

For galaxy formation studies HyZRGs are also cursed because their structures are aligned with their associated radio sources, suggesting that the collimated outflow and ionizing radiation from their AGN profoundly affect their parent galaxy host appearances at UV, blue and green wavelengths (McCarthy 1999, and Dey 1999; these proceedings). HyZRGs are very well suited for studying the effects of powerful AGN on ambient dense gas, including induced star formation (e.g., Bicknell et al. 1999), and may even be used as searchlights to investigate the properties of proto-galactic material in the early Universe (Cimatti et al. 1997; Villar-Martín et al. 1997).

Recent cosmological theories are providing additional incentives to use radio galaxies as probes to study the early Universe. Within standard Cold Dark Matter scenarios the formation of galaxies is a hierarchical and biased process. Large galaxies are thought to grow through the merging of smaller systems,

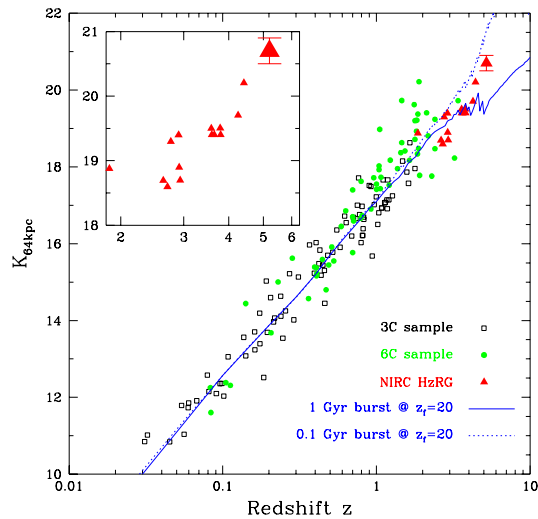


Figure 1. The Hubble $K - z$ diagram for HyZRGs. Filled triangles are Keck measurements of HzRGs from van Breugel et al. (1998), the large triangle is TN J0924–2201 at $z = 5.19$, and all other photometry is from Eales et al. (1997). Two stellar evolution models from Bruzual & Charlot (1999), normalized at $z < 0.1$, are plotted, assuming parameters as shown.

and the most massive objects form in over-dense regions, which will eventually evolve into the clusters of galaxies seen today (e.g., White 1997). It has also been suggested that the first massive black holes may grow in similar hierarchical fashion together with their parent galaxies (e.g., Kauffmann and Haehnelt 1999) or, because of time scale constraints, may precede galaxy formation and be primordial (e.g., Loeb 1993). To confront these theories it is therefore of great interest to find the progenitors of the most massive galaxies and their AGN (active massive black holes) at the highest possible redshifts and to study their properties and cosmological evolution.

While optical, ‘color-dropout’ techniques have been successfully used to find large numbers of ‘normal’ young galaxies (without dominant AGN) at redshifts even surpassing those of quasars and radio galaxies (Weymann et al. 1998; Hu et al. 1999), the radio and near-infrared selection technique has the additional advantage that it is unbiased with respect to the amount of dust extinction. HyZRGs are therefore also important laboratories for studying the large amounts of dust (e.g., Ivison et al. 1998) and molecular gas (Papadopoulos et al. 1999), which are observed to accompany the formation of the first forming massive galaxies. Indeed, a significant part of the scientific rationale for building future large mm-arrays is based on the expectation that to understand galaxy formation will ultimately require understanding of their cold gas and dusty environments.

Table 1. Radio Surveys

	WENSS	TEXAS	MRC
Frequency (MHz)	325	365	408
Sky region	$\delta > +29^\circ$	$-35.7^\circ < \delta < +71.5^\circ$	$-85^\circ < \delta < +18.5^\circ$
# of sources	229,576	67,551	12,141
Resolution	$54'' \times 54'' \cos \delta$	$10''$	$2.62 \times 2.86 \sec(\delta - 35.5^\circ)$
Position uncertainty (strong sources)	$1''.5$	$0''.5-1''$	$8''$
RMS noise	~ 4 mJy	20 mJy	70 mJy
Flux density limit	18 mJy	150 mJy	670 mJy
	NVSS	FIRST ^a	PMN
Frequency (MHz)	1400	1400	4850
Sky region	$\delta > -40^\circ$	$b > 45$	$-87.5^\circ < \delta < +10^\circ$
# of sources	1,814,748	550,000	50,814
Resolution	$45'' \times 45''$	$5'' \times 5''$	$4''.2$
Position uncertainty (strong sources)	$1''$	$0''.1$	$\sim 45''$
RMS noise	0.5 mJy	0.15 mJy	~ 8 mJy
Flux density limit	2.5 mJy	1 mJy	20 mJy

^aStill in progress.

Finally, it has been claimed that the (co-moving) space densities of the most powerful radio galaxies and quasars were much higher near $z \sim 2$, but that they drop off precipitously at even higher redshifts (Dunlop and Peacock 1990; Shaver et al. 1996). However, using recently completed studies of moderately faint radio galaxies Jarvis et al. (1999; these proceedings) have argued that there is *no* such evidence for a redshift cut-off and that these previous results have been biased due to unknown radio K-correction (radio spectral index) trends and associated selection effects.

For all these reasons HyZRGs have become very useful probes of the early Universe. Unfortunately in complete, flux-limited samples the vast majority of the sources will be relatively nearby, or at only modest higher redshifts. However, by employing the well-known ‘red radio color’ selection technique and choosing sources with ultra-steep radio spectra one can bypass most of the ‘local’ radio source population and efficiently identify radio galaxies at extremely higher redshift.

2. The Ultimate Ultra-Steep Spectrum Source Sample

With the advent of several new, large radio surveys (Table 1) such as the 325 MHz WENSS (Rengelink et al. 1997), the 365 MHz TEXAS (Douglas et al. 1996), the 1.4 GHz NVSS (Condon et al. 1998), the 1.4 GHz FIRST (Becker et al. 1995), MRC 408 MHz (Large et al. 1981) and the 4.85 GHz PMN

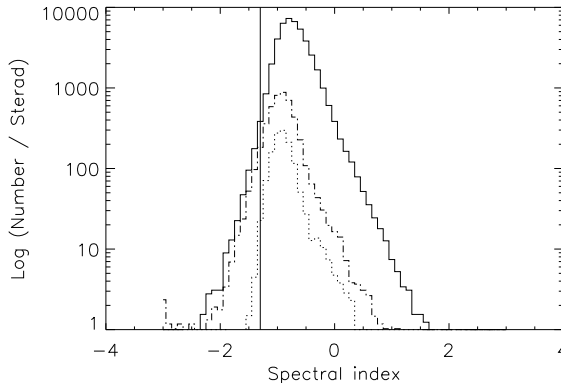


Figure 2. Logarithmic spectral index distribution for WENSS-NVSS (full line), Texas-NVSS (dot-dash line) and MRC-PMN (dotted line). The vertical line indicates the -1.3 cutoff used in our spectral index selection.

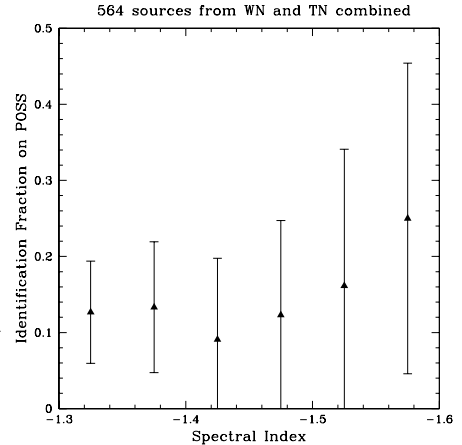


Figure 3. Identification fraction on the POSS as a function of spectral index for the combined WN and TN sample.

(Griffith et al. 1993) surveys it is now possible for the first time to define a large sample of USS sources with extremely steep radio continuum spectra ($\alpha \leq -1.3$, Fig. 2), and using 10 – 100 times lower flux density limits than has been possible before (Chambers et al. 1996; Röttgering et al. 1994; Blundell et al. 1998).

Using these surveys we constructed 3 sub-samples, covering different regions of the radio sky using the deepest low and high frequency surveys available in each area (Table 2). Our largest, and most complete sample is based on the WENSS survey at $\delta > 29^\circ$, together with the NVSS and FIRST surveys. In the remaining area covered by the northern hemisphere radio telescopes, we used the Texas survey at low frequencies, which produces a similar sample but at a higher flux density and is less complete. We also used two southern surveys to construct the first USS sample in the deep southern sky. More details about the samples are given in De Breuck et al. (2000a).

During the course of our optical and near-IR imaging and optical spectroscopy programs we have fine-tuned our selection technique. Previously it had been found that the identification fraction of radio galaxies decreases with spectral index (Tielens et al. 1979; Röttgering et al. 1995), which provided the rationale for using the USS source selection technique. With our ‘hyper-steep’ radio spectrum selection ($\alpha \leq -1.3$) most sources remain unidentified, at least on the POSS ($R \lesssim 20$). Only $\sim 15\%$ of the sources can be identified, usually with bright galaxy clusters, as indicated by the frequent overdensity of galaxies around them, and by X-ray detections (De Breuck et al. 2000a). This identification fraction appears to be independent of spectral index (Fig. 3), in support of the idea that these are mostly foreground objects.

This also explained why our initial optical imaging campaign on 3m–4m–class telescopes ($R \lesssim 24$) was not very succesful in finding R –band identifications. Furthermore, for the typically expected $R - K \sim 4$ values of HyZRGs, it would even be a challenge to detect most HyZRGs in the near–IR at Lick Observatory. We therefore decided to entirely skip the optical identification program and go straight to near–IR imaging at the Keck I telescope. This has produced, to date, a 100% identification rate with good photometric magnitudes to select HyZRG candidates using the Hubble $K - z$ diagram (Fig. 1).

We have now spectroscopically observed 30 faint USS HyZRG candidates with the following results. Only 5 of the sources have $z < 2$, 7 have $2 < z < 3$, 7 have $3 < z < 4$ and 2 sources have $z > 4$, including one at $z > 5$. At least 3 sources failed to yield redshifts, and were not detected in the continuum, despite ~ 1 hr integrations with LRIS, and may be at record hy redshifts, or are extremely obscured. We also found 6 sources with only a continuum detection and no emission–lines. These were all extremely compact USS sources, and may be moderately hy redshift ($1 < z < 3$) BL Lac objects, ‘emission–line free quasars’ (c.f., Fan et al. 1999), or even pulsars (which typically have $\alpha_{radio} \sim -1.6$, Kaplan et al. 1998, and are faint optically; Martin et al. 1998).

Table 2. USS samples

Sample	Density sr^{-1}	Spectral Index	Flux Limit mJy	# of Sources
WN	151	$\alpha_{325}^{1400} \leq -1.30$	$S_{1400} > 10$	343
TN	48 ^a	$\alpha_{365}^{1400} \leq -1.30$	$S_{1400} > 10$	268
MP	26	$\alpha_{408}^{4800} \leq -1.20$	$S_{408} > 700$; $S_{4850} > 35$	58

^aDue to the characteristics of the Texas survey, the TN sample is only $\sim 30\%$ complete.

3. The Highest-Redshift Radio Galaxies

3.1. TN J1338–1942 at $z = 4.11$

The first $z > 4$ USS radio galaxy discovered by us was TN J1338–1942. The initial identification was made with the ESO 3.6m at R–band, and subsequent spectroscopy with that same telescope showed that the radio galaxy has a redshift of $z = 4.11 \pm 0.02$, based on a strong detection of $\text{Ly}\alpha$, and weak confirming C IV λ 1549 and He II λ 1640 (De Breuck et al. 1999a).

Subsequently we obtained a deep K–band image (rest–frame B–band) at Keck, shown in Figure 4 overlaid with a VLA radio image (De Breuck et al. 1999b). The radio source is an asymmetric double, with a very bright NW hotspot ($S_{4.7\text{GHz}} = 22$ mJy; $\alpha_{4.7\text{GHz}}^{8.5\text{GHz}} \sim -1.6$) coincident with the peak of the K–band emission. This hotspot has a very faint radio companion with a flatter spectrum ($S_{4.7\text{GHz}} = 0.3$ mJy; $\alpha_{4.7\text{GHz}}^{8.5\text{GHz}} \sim -1.0$) at $1''.4$ to the SE which we identify as the probable nucleus. Thus the AGN and rest–frame optical (continuum and $\text{Ly}\alpha$) emission may not be co–centered. This resembles the $z = 3.800$ radio galaxy 4C41.17 (van Breugel et al. 1999). A possible reason for this might be

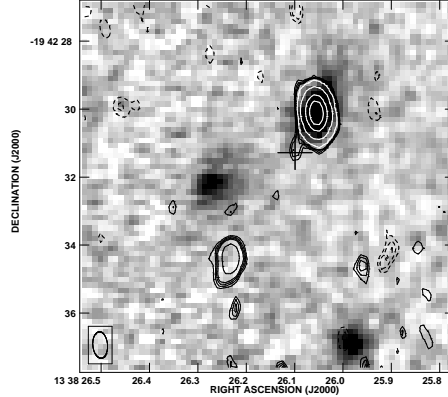


Figure 4. 4.85 GHz VLA radio contours overlaid on a Keck K -band image of TN J1338–1942.

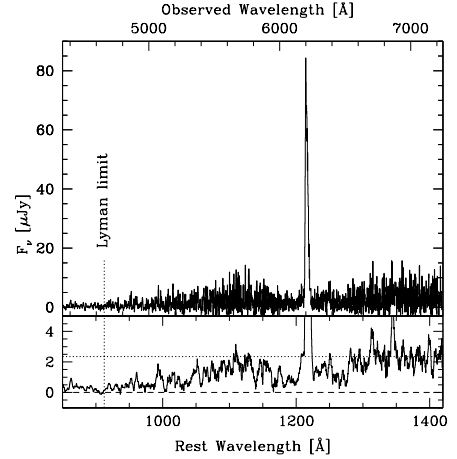


Figure 5. VLT spectrum of TN J1338–1942 at $z = 4.11$.

that the central region is obscured by dust. Such asymmetric radio sources are not uncommon, even in the local Universe, and are usually thought to be due to strong interaction of one of its radio lobes with very dense gas (e.g., McCarthy et al. 1991; Feinstein et al. 1999).

A high signal-to-noise spectrum was also obtained with the VLT Antu telescope (De Breuck et al. 1999b). The spectrum is dominated by the bright $\text{Ly}\alpha$ line ($W_{\text{Ly}\alpha}^{\text{rest}} = 210\text{\AA}$) which shows deep and broad ($\sim 1400\text{ km s}^{-1}$) blue-ward absorption. The latter is probably due to resonant scattering by cold HI gas in a turbulent halo surrounding the radio galaxy and has also been seen several other HyZRGs (van Ojik et al. 1996; Dey 1999). The continuum is relatively bright ($F_{1400} \sim 2\mu\text{Jy}$) and if all due to young O–B stars this would imply a total SFR of several hundred M_{\odot}/yr , resembling 4C41.17, and suggesting that TN J1338–1942 may be another HyZRG in which induced star formation might occur (c.f., Bicknell et al. 1999).

In Table 3 we have listed the $\text{Ly}\alpha$ properties of the known 7 most distant radio galaxies for which high quality optical slit spectroscopy data taken with Keck or the VLT are available. We have assumed $H_0 = 65\text{ km s}^{-1}\text{Mpc}^{-1}$, $q_0 = 0.15$, and $\Lambda = 0$. The $\text{Ly}\alpha$ fluxes are as measured i.e., uncorrected for blue-ward absorption. TN J1338–1942 is the most luminous $\text{Ly}\alpha$ galaxy and, after 4C41.17, also the brightest (in similar apertures). In all cases the brightest $\text{Ly}\alpha$ emission occurs on scale sizes of $1'' - 2''$, comparable to those of the brightest radio structures. 4C41.17 is known to have a very extended halo (Chambers et al. 1990) and the total size quoted is a lower limit, based on the deep (9 hrs) Keck spectropolarimetry data from Dey et al. (1997).

3.2. TN J0924–2201 at $z = 5.19$

TN J0924–2201 is one of the steepest spectrum sources in our USS sample ($\alpha_{365\text{MHz}}^{1.4\text{GHz}} = -1.63$) and therefore was one of our primary targets for near-IR identification. A deep K -band image at Keck showed indeed a very faint ($K =$

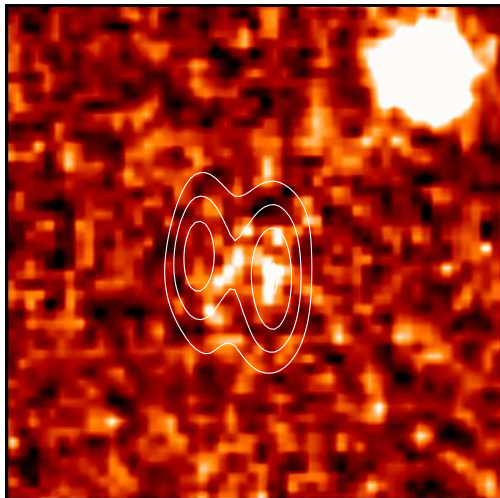


Figure 6. Keck/NIRC K -band image of TN J0924–2201, with radio contours superposed.

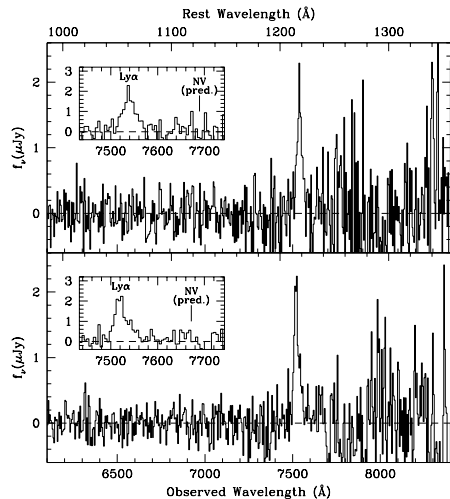


Figure 7. Keck spectra of TN J0924–2201 at $z = 5.19$ on two different nights.

21.3 ± 0.3), multi-component object at the position of the small ($1''.2$) radio source (Fig. 6). The expected redshift on the basis of the $K - z$ diagram was $z > 5$, and spectroscopic observations at Keck showed that this was indeed the case, based on a single emission line at $\lambda \sim 7530 \text{ \AA}$ which we identified as $\text{Ly}\alpha$ at $z = 5.19$ (van Breugel et al. 1999; none of the $z > 5$ galaxies have more than one line detection).

Among all radio selected HyZRGs TN J0924–2201 is fairly typical in radio luminosity, equivalent width and velocity width (Table 2). It does have the steepest radio spectrum, consistent with the $\alpha - z$ relationship for powerful radio galaxies (e.g., Röttgering et al. 1997), and also has the smallest linear size. The latter may be evidence of its ‘inevitable youthfulness’ or a dense confining environment, neither of which would be surprising because of its extreme redshift (Blundell & Rawlings 1999; van Ojik et al. 1997). Among the radio selected HyZRGs TN J0924–2201 appears underluminous in $\text{Ly}\alpha$, together with 8C 1435+63, which might be caused by absorption in an exceptionally dense cold and dusty medium. Evidence for cold gas and dust in several of the most distant HyZRGs has been found from sub-mm continuum and CO-line observations (e.g., Ivison et al. 1998; Papadopoulos et al. 1999).

The second highest redshift radio galaxy currently known listed in Table 3 is VLA J123642+621331 at $z = 4.42$ (Waddington et al. 1999). This source was not USS selected and therefore provides an interesting alternate view on the possible selection effects of our method of finding HyZRGs. The source is an asymmetric double and although its radio luminosity is about a factor 1000 times lower than that of its much more luminous brothers at similar redshifts, it still qualifies as a FR II-type, though with a radio luminosity close to the FRI / FR II break at 408 MHz ($P_{408} \sim 3.2 \times 10^{26} \text{ W Hz}^{-1}$). Its radio spectrum is steep ($\alpha_{8.4\text{GHz}}^{1.4\text{GHz}} \sim -1.0$, using the flux densities given by Waddington et al.), but not as steep as our USS selected HyZRGs, and the $\text{Ly}\alpha$ luminosity is a factor 5 – 10

times less. Apart from the luminosity these properties are not hugely different from expected on the basis of radio selection and indicate that less extreme steep spectrum selected samples ($\alpha < -1.0$) at much lower flux densities ($\lesssim 1 mJy$) might be used to find many more (hundreds, thousands ?) HyZRGs at very hy redshifts (though with much lower efficiency, we suspect, than USS selected samples).

Table 3. Physical Parameters of the Highest HyZRGs

Name	z	$L_{Ly\alpha}^a$	L_{365}^a	α_{365}^{1400}	$W_{Ly\alpha}^{rest}$	$\Delta_{Ly\alpha}^a$	Size ^a	Ref. ^b
TN J0924–2201	5.19	1.3	7.5	−1.63	>115	1500	8	WvB99
VLA J1236+6213	4.42	0.2	0.0035	−0.96	>50	440		Wad99
6C 0140+326	4.41	16	1.3	−1.15	700	1400	19	DeB00
8C 1435+63	4.25	3.2	11	−1.31	670:	1800	28	Spin95
TN J1338–1942	4.11	25	2.3	−1.31	200	1000	37	DeB99
4C 41.17	3.798	12	3.3	−1.25	100	1400	99	Dey97
4C 60.07	3.79	16	4.1	−1.48	150	2900:	65	Röt97

^aIn units of 10^{43} erg s^{−1} ($L_{Ly\alpha}$), 10^{36} erg s^{−1} Hz^{−1} (L_{365}), restframe km s^{−1}, kpc respectively)

^bMost recent references quoted only: WvB99 = van Breugel et al. (1999); Wad99 = Waddington et al. (1999); DeB00 = De Breuck et al. (2000b); Spin95 = Spinrad et al. 1995; DeB99 = De Breuck et al. (1999a, b); Dey97 = Dey et al. (1997); Röt97 = Röttgering et al. (1997).

Our observations of TN J0924–2201 extend the Hubble $K - z$ diagram for powerful radio galaxies to $z = 5.19$, as shown in Figure 1. Simple stellar evolution models are shown for comparison. Despite the enormous k -correction effect (from U_{rest} at $z = 5.19$ to K_{rest} at $z = 0$) and strong morphological evolution (from radio-aligned to elliptical structures), the $K - z$ diagram remains a powerful phenomenological tool for finding radio galaxies at extremely hy redshifts. Deviations from the $K - z$ relationship may exist (Eales et al. 1997; but see McCarthy 1999), and scatter in the $K - z$ values appears to increase with redshift, but this may in part be caused by limited signal-to-noise or emission-line contamination.

The clumpy U_{rest} morphology resembles that of other HyZRGs (van Breugel et al. 1998; Pentericci et al. 1998) and if it is dominated by star light we derive a SFR of $\sim 200 M_{\odot} \text{ yr}^{-1}$, without any correction for extinction, which may be a factor of several. TN J0924–2201 may be a massive, active galaxy in its formative stage, in which the SFR is boosted by jet-induced star formation (Dey et al. 1997; van Breugel et al. 1999; Bicknell et al. 1999). For comparison other, ‘normal’ star forming galaxies at $z > 5$ have 10 – 30 times lower SFR ($\sim 6 - 20 M_{\odot} \text{ yr}^{-1}$; Dey et al. 1998; Weymann et al. 1998; Spinrad et al. 1998).

At $z = 5.19$ TN J0924–2201 is currently the most distant AGN known, surpassing even quasars for the first time since their discovery 36 years ago. The presence of AGN at such early epochs in the Universe (< 1 Gyr in most cosmogonies) poses interesting challenges to common theoretical wisdom, which assumes that they are massive (billion solar mass), active black holes. The

question how these can form so shortly after the putative Big Bang may prove even more challenging than that of the formation of galaxies (e.g., Loeb 1993; Silk & Rees 1998).

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